

## Cosmological model: from initial conditions to structure formation

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**Summary.** — Observational cosmology is on the verge of new discoveries that will change the essence of our world-view. The matter concerns origin of initial conditions and physics of dark matter.

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### 1. – Identification problem

A century of cosmology has led us to a new understanding of the Universe. Today we know the model at large scales. *Per aspera ad astra*. After many years of hypotheses and markets of models we now have the standard cosmological model, yet separated from what we have at small scales – the standard model of elementary particles. Both models progressively converge and interact with each other leading us to a joint physical model of the World we are a part of.

The progress in cosmology is ensured by observations. This creates identification problem. It is a specific feature of astronomy. Astronomers *see* structures unknown to physicists. They cannot touch or test them, they can learn only general properties of observed matters assuming some theoretical extrapolations (General Relativity, atomic physics, etc.). On the contrary, physicists need experiment to judge things. To understand what astronomers see, physicists are looking in labs for what is unknown to them, since there is not enough information about the target. In this way the problem of identification arises.

What do astronomers see?

They observe structures made of invisible matter, the *dark matter*. DM does not interact with light, generally - with luminous matter, or baryons. How is DM observed

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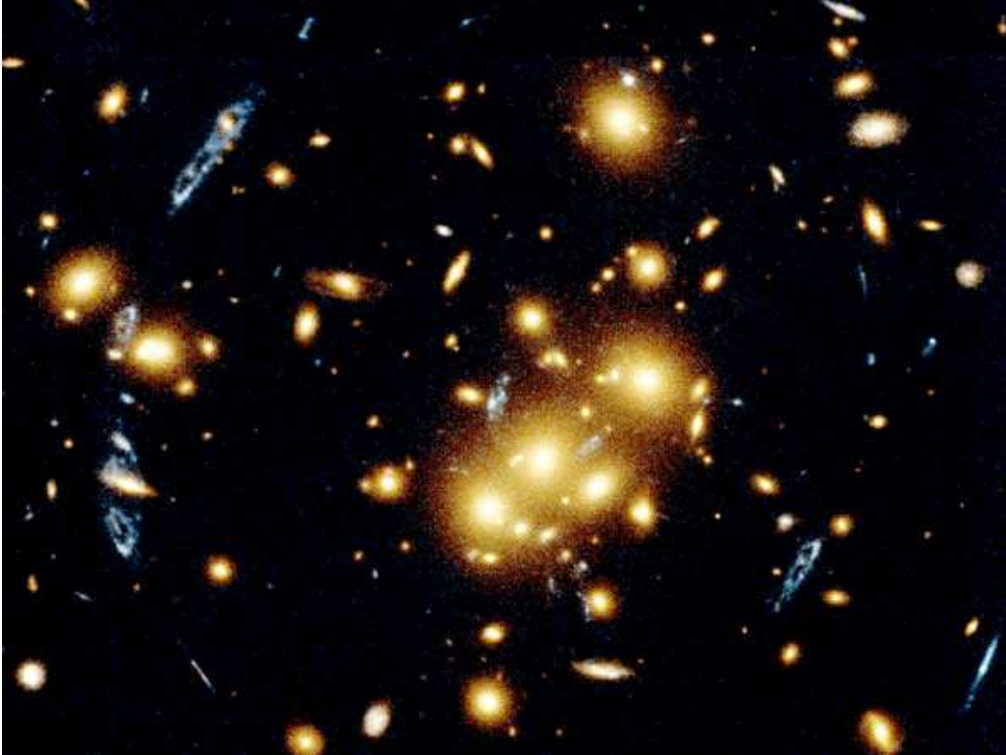


Fig. 1. – Hubble Space Telescope photo of a sky region in the direction of cluster of galaxies 0024 + 1654.

then? Through its gravitational influence on visible matter. Fortunately, light is there where DM concentrations are.

Fig. 1 shows a region of sky in the direction of one of DM *halos*, the non-linear DM concentration gravitationally bound in all three directions with total mass  $\sim 10^{14} M_{\odot}$ . We see optical galaxies captured by gravitational field of this concentration, X-ray gas residing at the bottom of the gravitational well, and a multi-image of one of the background galaxies that happened to be on the line of sight of the DM halo and was distorted by its gravitational field.

We study spatial distribution of DM halos analyzing galaxy catalogs and quasar absorption lines. Besides, the DM surface mass density can be reconstructed via its gravitational weak lensing action on numerous background galaxies. So, there is more than enough independent probes of dark mass inside and beyond DM halos. We can state that the mean contrast of DM density field is larger than unity at small scale ( $< 10 \text{ Mpc}$ ) still remaining less than unity at large scale ( $\geq 10 \text{ Mpc}$ ). Accordingly, we do not find DM halos exceeding  $10^{15} M_{\odot}$ .

This is the current DM density field. We are lucky to have a map of much younger matter density field using CMB anisotropy. That time ( $z \sim 1000$ ) the mean density contrast was  $\sim 10^{-5}$ , and no halos had formed yet. Having these two pictures of cosmic matter distribution at different epochs of its evolution and assuming that only gravity is responsible for such evolution, we can obtain the DM energy-momentum tensor.

What are DM properties?

Actually, they are very simple. DM is non-relativistic *weakly interacting massive particles* with cosmological density five times higher than that of baryons. WIMPs should be cold (non-relativistic) long before the equality epoch to be able to form the structure that we observe today. Owing to such simple properties, DM has straightforwardly affected the development of the Universe gravitational potential. The DM density contrast was increasing in time due to gravitational instability. Baryons, after they decoupled from radiation, were captured into gravitational wells of DM concentrations. That is why light is there where DM is, although DM particles do not interact with light. Thanks to this remarkable feature of gravitational instability it is possible to study amount, state and distribution of DM in observations ranging from radio to X-ray bands. Contemporary physics does not know particles with DM properties. It is necessary to go beyond the standard model. But how and in which direction? What should we look for?

The analysis of large scale structure in the Universe has revealed that the amount of non-relativistic DM entering structure is small. The overall mass density of all particles which have been involved in the process of gravitational clustering, cannot exceed 30% of the critical density. Massive neutrino contribute less than few percent to the matter budget. At the same time the characteristics of CMB anisotropy have evidenced the flat spatial geometry of our Universe. It means that the rest 70% of the critical density should be in the form that takes no part in gravitational clustering. What are the properties of such a stable medium which is not perturbed by gravitational potential of the structure and remains essentially unclustered?

Theory gives a clear answer to this question – the pressure-to-energy ratio of this medium,  $w \equiv p_{DE}/\epsilon_{DE}$ , should satisfy the following condition:

$$(1) \quad |1 + w| < 1 .$$

Only under this inequality the medium remains Lorentz-invariant and invariable both in space and time. We call it *dark energy*. This is all we know about DE.

It is crucial that the process of gravitational instability could be launched in the Friedmann Universe only if the seed density perturbations were present since the very beginning. The existence of primordial cosmological perturbations has nothing to do with DM or any other particles. These are the total density perturbations that were produced by the Big Bang physics. Thus, another important problem arises, the problem of origin of the seed density perturbations which have developed dynamically into DM structures.

These hot topics – searching for unknown matter and determining the initial conditions for structure formation – display new physics and are expected to be solved in near future. In this review we dwell upon them.

## 2. – Geometry of late and early Universe

The observed structure of the Universe is a product of start conditions and evolution of matter density field. Up-to-date observational data made it possible to determine characteristics of the density field at different epochs of its development. It allowed us to separate information about the initial conditions and development conditions, thus giving rise to independent investigations of the early and late Universe physics.

In modern cosmology the term "early Universe" stands for the final period of the inflationary *Big Bang stage* with subsequent transition to hot period of cosmological expansion. Currently we have no model of the early Universe as we do not know BBS pa-

rameters (there are only upper bounds, see eq. (14)). However, we have a well-developed theory of quantum-gravitational generation of the cosmological perturbations. Using this theory, we can derive the spectra of primordial density perturbations and cosmic gravitational waves as functions of cosmological parameters, and constrain the latter if the spectra are known.

The reason why we still have no generally-accepted model of the early Universe stems from stable predictions of BBS inflationary paradigm, that are obtained in a wide class of model parameters. Namely, the generated spectra are almost flat, the amplitude of the cosmological gravitational waves is relatively small, etc. Detection of the cosmological gravitational waves would give crucial information about the early Universe. This discovery may come in case the PLANCK experiment succeeds.

Our knowledge of the late Universe is quite opposite. We have rather precise model – we know the main matter components and cosmological parameters, the evolution of the Universe and theory of structure formation. But we do not understand how the matter components have originated.

The known properties of the visible Universe allow us to describe the geometry of both, late and early Universe, in the framework of the perturbation theory. There is a small parameter  $\sim 10^{-5}$ , the amplitude of cosmological perturbations.

The main tool of geometry is metric tensor. To zeroth order the Universe is Friedmannian and described with only one time function – the scale factor  $a(t)$ . The first order is a bit more complicated. The metrics perturbations are the sum of three independent modes – the scalar one  $S(k)$ , the vector one  $V(k)$ , and the tensor one  $T(k)$ , each of them being described by its spectrum, the function of the wave number  $k$ . The scalar mode describes the cosmological density perturbations, the vector mode is responsible for vortical matter motions and the tensor mode presents the gravitational waves. If the first order fields are Gaussian then the entire geometry of our Universe is described with only four positively defined functions,  $a(t)$ ,  $S(k)$ ,  $T(k)$  and  $V(k)$ . Currently we know the first two functions in some ranges of their definition.

BBS was a catastrophic process of rapid expansion accompanied by intensive time varying gravitational field. Under this gravitational action the small-scale cosmological perturbations of metric and density were being parametrically born from vacuum fluctuations. It is very general and fundamental effect of creation of any massless degree of freedom in external coupled non-stationary field.

Available observational data confirm the quantum-gravitational origin of seed density perturbations responsible for structure formation in the Universe. It is a good example of the solution of measurability problem in quantum field theory. The basic properties of the perturbation fields generated according to this mechanism are the following: the Gaussian statistics (random distribution in space), the preferred time phase ("growing" branch of evolution), the absence of characteristic scales in a wide range of wavelengths, a non-zero amplitude of the gravitational waves. The latter is crucial for building-up the BBS model as gravitational waves couple the simplest way to the background scale factor.

The development of  $S$ -mode has resulted in formation of galaxies and other astronomical objects. The CMB anisotropy and polarization have emerged long before under the joint action of all three perturbation modes ( $S, T$  and  $V$ ) on the photon distribution. Joint analysis of the observational data on galaxy distribution and the CMB anisotropy allowed us to relate  $S$  and  $T + V$  modes. Making use of the fact that the sum  $S + T + V \simeq 10^{-10}$  is known from the CMB anisotropy, we obtain the upper bound for

TABLE I. – *Basic cosmological parameters.*

Hubble parameter	$h = 0.7$
CMB temperature	$T = 2.725K$
3-space curvature	$\Omega_\kappa = 0$
cosmological density of baryons	$\Omega_B = 0.05$
cosmological density of dark matter	$\Omega_{DM} = 0.23$
cosmological density of dark energy	$\Omega_\Lambda = 0.7$
power-spectrum index	$n_S = 0.96$

the vortical and tensor perturbation modes in the visible Universe:

$$(2) \quad \frac{T + V}{S} < 0.2$$

In case the latter inequality were violated the density perturbation value would not be sufficient to form the observed structure. The detection of  $T$  and/or  $V$  (e.g. cosmological magnetic field) will become possible only with increase of observational precision.

### 3. – Is DE a massive field ?

Let us consider zero order geometry more detailed.

Table I presents average values of the cosmological parameters obtained from astronomical observations (with 10% accuracy). With these parameters, we obtain from the Friedmann equations the Hubble function,  $H \equiv \dot{a}/a$ , and its time derivative,  $\gamma \equiv -\dot{H}/H^2$ :

$$(3a) \quad \frac{H}{H_0} = 10^{61} \frac{H}{M_P} = \left( \frac{10^{-4}}{a^4} + \frac{0.3}{a^3} + 0.7 \right)^{1/2},$$

$$(3b) \quad \gamma = \frac{d \ln(M_P/H)}{d \ln a} = \frac{3(\epsilon + p)}{2\epsilon} = \frac{2 \cdot 10^{-4} + 0.4a}{10^{-4} + 0.3a + 0.7a^4},$$

where  $H_0^{-1} = 14 \text{Gyr} = 10^{33} \text{eV}^{-1}$  is the inverse Hubble constant,  $M_P = \ell_P^{-1} = 10^{19} \text{GeV} = 10^{33} \text{cm}$  is the Planck mass (or inverse Planck scale, hereafter  $c = \hbar = 1$ ).  $\gamma$ -function relates the Hubble size of the Universe with its expansion factor.

Eqs.(3) evidence that all transitions from radiation to matter and to DE dominated expansions occurred at small energies pretty well known to atomic physics ( $T_{rad} = 2.5 \cdot 10^{-4}/a \text{ eV}$ ). When extrapolating eqs.(3) to earlier times (or higher energies) we learn the following properties of our Universe:

- The Universe is large,  $(H_0 \ell_P)^{-1} \sim 10^{61}$ . At the beginning of the expansion (2) the physical size of the Universe was a factor  $10^{30}$  higher than Planckian size ( $a/H_0 \gg$  the current length of relic quanta). Such a big factor can be explained by a pre-existed short inflationary stage with  $\gamma < 1$  (BBS).
- The cosmological perturbations are uncausal (scales enter horizon at  $\gamma > 1$ ). Eqs.(2) describe decay of  $\gamma$  from 2 to 0.4. To explain uncausality, one has to admit a pre-existed period of cosmological expansion with  $\gamma$  rising from values smaller than unity (BBS).

Existence of BBS in the early Universe prompts us a solution of DE problem. Indeed, within 14 billion years the Universe was at least twice in state of inflation ( $\gamma < 1$ , by the definition). There could be more than two stages with  $\gamma < 1$ . Therefore, we guess that similar physical reasons could be responsible for different inflationary stages.

Actually, we study the physics of the final period of BBS when analyzing the large scale structure in the Universe and the products of BBS inflaton decay (photons, baryons, etc.). On the other hand, we witness the beginning of the DE *stage* of new inflation. Assuming similar physical reasons causing both stages (BBS and DES) we come to conclusion that each of these stages must have the beginning and the end.

Let us illustrate it on the example of simplest inflatons – *weakly interacting massive fields* <sup>(1)</sup>. Each inflationary stage starts with the beginning of appropriate WIMF domination at slow-roll period of its evolution, and ends by transferring either to the WIMF oscillations (domination of the non-relativistic WIMPs) or to the WIMF decay into massless degrees of freedom.

In this scenario the history of the Universe represents the history of relaxation of massive fields. How to verify this simple idea? One of the possibilities can be measuring the  $w$  and  $\gamma$  parameters. Say, if DE is a  $\phi$ -scalar WIMF then the prediction is  $1 + w = 0.053 \cdot (M_P/\phi)^2$ , which can be measured both in sign and value.

#### 4. – In search for DM particles

DM are WIMPs which were non-relativistic long before the structure formation in the Universe (back to  $T_{rad} > 10$  keV). We do not know whether WIMPs have decoupled from the thermal bath of particles or originated evolutionary from some WIMF having never been in equilibrium with other particles.

Currently, there are several hypotheses on the origin of DM, but none of them has been confirmed so far. There exist observational arguments indicating that the DM mystery is related with baryon asymmetry in the Universe. Two of these arguments are the most appealing:

- The energy densities of both non-relativistic components, baryons and DM, are close to each other now and at the moment of their generation
- The characteristic scales of spatial distributions of baryon and DM are identical (the cosmological horizon of equal densities of radiation and matter = the sound horizon of hydrogen recombination)

However, now there are no generally-accepted theories of the DM and baryon asymmetry. Where is dark matter?

We know that luminous constituent of matter is observed as stars residing in galaxies of different masses and in the form of X-ray gas in clusters of galaxies. However, a greater amount of ordinary matter is contained in rarefied intergalactic gas with temperatures from several to hundred eV and also in MACHO-objects which are the compact remnants of star evolution and the objects of small masses. Since these structures mostly have low luminosity they are traditionally called "dark baryons".

Several scientific groups (MACHO, EROS and others) carried out the investigation of the number and distribution of compact dark objects in the halo of our Galaxy, which was

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<sup>(1)</sup> Recall two important periods of WIMF evolution: friction domination (the slow-roll period) and free oscillations (the WIMP period).

TABLE II. – *Candidates for non-baryonic dark matter particles.*

candidate	mass
gravitons	$10^{-21}$ eV
axions	$10^{-5}$ eV
”sterile” neutrino	10 keV
mirror matter	1 GeV
neutralino	100 GeV
super-massive particles	$10^{13}$ GeV
monopoles and defects	$10^{19}$ GeV
primordial black holes	$10^{-16} - 10^{-7} M_{\odot}$

based on micro-lensing events. The combined analysis resulted in an important bound – no more than 20% of the entire halo mass is contained in the MACHO-objects of masses ranging from the Moon to star masses. The rest of the halo dark matter consists of unknown particles.

Where else is non-baryonic DM hidden?

The development of high technologies in observational astronomy of the 20th century allowed us to get a clear-cut answer to this question – non-baryonic DM is contained in gravitationally bound systems (DM halos). DM particles are non-relativistic and weakly interacting. Unlike baryons, they do not dissipate whereas baryons are radiationally cooled and settle near the halo centers attaining rotational equilibrium. DM stays distributed around the visible matter of galaxies with characteristic scale  $\sim 200$  kpc. For example, in the Local Group which comprises Andromeda and Milky Way, more than a half of all DM belongs to these two large galaxies.

Particles with required properties are absent in the standard model of particle physics. An important parameter that cannot be determined from observations due to the Equivalence Principle is the mass of particle. In this situation the experiment ”goes there, do not know where” (after the Russian fairy tale). The main candidates are listed in Table II in ascending order of their rest masses.

One of the versions on agenda – the neutralino hypothesis – rises from minimal supersymmetry. This hypothesis can be verified in CERN at LHC that will run in 2008. The expected mass of these particles is  $\sim 100$  GeV, and their density in our Galaxy is a particle per cup of coffee.

DM particles are being searched in many experiments all over the world. Interestingly, the neutralino hypothesis can be independently verified both in underground experiments on elastic scattering and by indirect data on neutralino annihilation in Galaxy. So far the positive signal has been found only in one of the underground detectors (DAMA), where a season signal of unknown origin has been observed for several years now. But the range of masses and cross-sections associated with this experiment has not been confirmed in other experiments, which makes reliability and meaning of the results quite questionable.

Neutralino give an important possibility of indirect detection by their annihilation gamma-ray flux. During the process of hierarchic clustering these particles could form mini-halos of the Earth masses and characteristic sizes comparable to that of the Solar System. Some of these mini-halos could stay intact till now. With high probability the Earth itself is inside one of these halos where the particle density is as much as tens of times higher than the mean halo density. Hence, the probability of both direct and

indirect detection of DM in our Galaxy gets higher. Availability of so different search techniques gives a solid hope that the physical nature of at one version of DM will soon be verified.

## 5. – In the beginning was sound

Let us consider the first order geometry in more detail.

The effect of the quantum-gravitational generation of massless fields is well-studied. Matter particles can be created with this effect (see [1, 2] etc.) (although the background radiation photons emerged as a result of the BBS proto-matter decay in the early Universe). The gravitational waves [3] and the density perturbations [4] are generated in the same way since they are massless fields and their creation is not suppressed by the threshold energy condition. The problem of the vortical perturbation creation is waiting for its researchers.

The theory of the  $S$  and  $T$  perturbation modes in the Friedmann Universe reduces to a quantum-mechanical problem of independent oscillators  $q_k(\eta)$  in the external parametrical field  $\alpha(\eta)$  in Minkovski space with time coordinate  $\eta = \int dt/a$ . The action and the Lagrangian of the elementary oscillators depend on their spatial frequency  $k \in (0, \infty)$ :

$$(4a) \quad S_k = \int L_k d\eta,$$

$$(4b) \quad L_k = \frac{\alpha^2}{2k^3} (q'^2 - \omega^2 q^2).$$

A prime denotes derivative with respect to time  $\eta$ ,  $\omega = \beta k$  is the oscillator frequency,  $\beta$  is the speed of the perturbation propagation in the vacuum-speed-of-light units (henceforth, the sub-index  $k$  for  $q$  is omitted). In the case of the  $T$  mode  $q \equiv q_T$  is a transversal and traceless component of the metric tensor,

$$(5) \quad \alpha_T^2 = \frac{a^2}{8\pi G}, \quad \beta = 1.$$

In the case of the  $S$  mode  $q \equiv q_S$  is a linear superposition of the longitudinal gravitational potential (the scale factor perturbation) and the potential of the 3-velocity of medium times the Hubble parameter [4]:

$$(6) \quad q_S = A + Hv, \quad \alpha_S^2 = \frac{a^2 \gamma}{4\pi G \beta^2},$$

where  $A \equiv \delta a/a$ ,  $v \equiv \delta \phi / \dot{\phi}$ .

As it is seen from eq. (5), the field  $q_T$  is fundamental, because it is minimally coupled with background metrics and does not depend on matter properties (in General Relativity the speed of gravitational waves is equal to the speed of light). On the contrary, the relation between  $q_S$  and the external field (6) is more complicated: it includes both derivatives of the scale factor and some matter characteristics (e.g. the speed of perturbation propagation in the medium). We do not know anything about the proto-matter in the Early Universe. There are only general suggestions concerning this problem.



Commonly, ideal medium is considered with the energy-momentum tensor depending on the energy density  $\epsilon$ , the pressure  $p$ , and the 4-velocity  $u^\mu$ . For the  $S$  mode, the 4-velocity is potential and represented as a gradient of the 4-scalar  $\phi$ :

$$(7) \quad T_{\mu\nu} = (\epsilon + p)u_\mu u_\nu - pg_{\mu\nu}, \quad u_\mu = \phi_{,\mu}/w,$$

where a comma denotes the coordinate derivative, and  $w^2 = \phi_{,\nu}\phi_{,\mu}g^{\mu\nu}$  is a normalizing function. The speed of sound is given by "equation of state" and relates comoving perturbations of the pressure and energy density:

$$(8) \quad \delta p_c = \beta^2 \delta \epsilon_c,$$

where  $\delta X_c = \delta X - v\dot{X}$ , and  $v \equiv \delta\phi/w$  is the potential of the 3-velocity of medium.

In the linear order of the perturbation theory the ideal medium concept is equivalent to the field concept where the Lagrangian density  $L = L(w, \phi)$  is ascribed to the material field  $\phi$  [4]- [6]. In the field approach the speed of the perturbation propagation is found from equation:

$$(9) \quad \beta^{-2} = \frac{\partial \ln |\partial L / \partial w|}{\partial \ln |w|},$$

which also corresponds to eq. (8). To zeroth order,  $\beta$  is a function time. However, in most models of the early Universe one usually assumes  $\beta \sim 1$  (e.g. at the radiation-dominated stage  $\beta = 1/\sqrt{3}$ ).

The evolution of the elementary oscillators is given by Klein-Gordon equation:

$$(10) \quad \bar{q}'' + (\omega^2 - U)\bar{q} = 0,$$

where

$$(11) \quad \bar{q} \equiv \alpha q, \quad U \equiv \frac{\alpha''}{\alpha}.$$

The solution of eq.(10) has two asymptotics: an adiabatic one ( $\omega^2 > U$ ) when the oscillator freely oscillates with the excitation amplitude being adiabatically damped ( $|q| \sim (\alpha\sqrt{\beta})^{-1}$ ), and a parametric one ( $\omega^2 < U$ ) when the  $q$  field freezes out ( $q \rightarrow const$ ). The latter conditions in respect to quantum field theory implies a parametrical generation of a pair of particles from the state with an elementary excitation (see Fig. 2).

Quantitatively, the spectra of the generated perturbations depend on the initial state of the oscillators:

$$(12) \quad T \equiv 2\langle q_T^2 \rangle, \quad S \equiv \langle q_S^2 \rangle,$$

where the field operators are given in the parametrical zone ( $q \sim const$ ). The factor 2 in the tensor mode expression is due to two polarizations of gravitational waves. The state  $\langle \rangle$  is considered to be a ground state, i.e. it corresponds to the minimal level of the initial oscillator excitation. This is the basic hypothesis of the Big Bang theory. In case the adiabatic zone is there, the ground (vacuum) state of the elementary oscillators is unique [7].

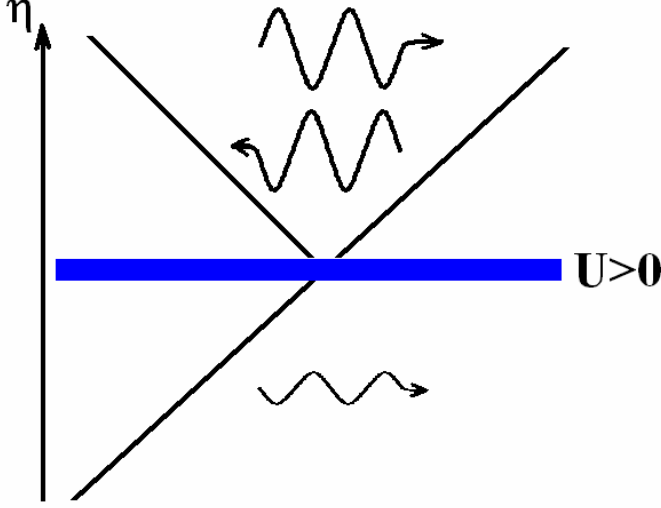


Fig. 2. – Illustration of solution of scattering problem for eq. (10).

Thus, assuming that the function  $U$  grows from zero with time (i.e. the initial adiabatic zone is followed by the parametric one) and  $\beta \sim 1$ , we obtain a universal and general result for the  $T(k)$  and  $S(k)$  spectra:

$$(13) \quad T = \frac{4\pi(2-\gamma)H^2}{M_P^2}, \quad \frac{T}{S} = 4\gamma,$$

where  $k \simeq aH$  specifies the moment of creation ( $\omega^2 = U$ ). As it is seen from eq. (13), the theory does not discriminate the  $T$  from  $S$  mode. It is the value of the factor  $\gamma$  in the creation period that matters when we relate  $T$  and  $S$ .

From the observed fact that the  $T$  mode is small in our Universe (see eq. (2)) we obtain the upper bound on the energetic scale of the Big Bang and on the parameter  $\gamma$  in the early Universe:

$$(14) \quad H < 10^{13} GeV, \quad \gamma < 0.05.$$

The latter condition implies that BBS was just inflation ( $\gamma < 1$ ).

We have important information on phases: the fields are generated in certain phase, only the growing evolution branch is parametrically amplified. Let us illustrate it for a scattering problem, with  $U = 0$  at the *initial* (adiabatic) and *final* (radiation-dominated,  $a \propto \eta$ ) evolution stages (see Fig. 2).

For either of the two above-mentioned stages the general solution is

$$(15) \quad \bar{q} = C_1 \sin \omega \eta + C_2 \cos \omega \eta,$$

where the constant operators  $C_{1,2}$  yield the amplitudes of the "growing" and "decaying" solutions. In the vacuum state the initial time phase is arbitrary:  $\langle |C_1^{(in)}| \rangle = \langle |C_2^{(in)}| \rangle$ . However, the solution of the evolution equations yields that only the growing

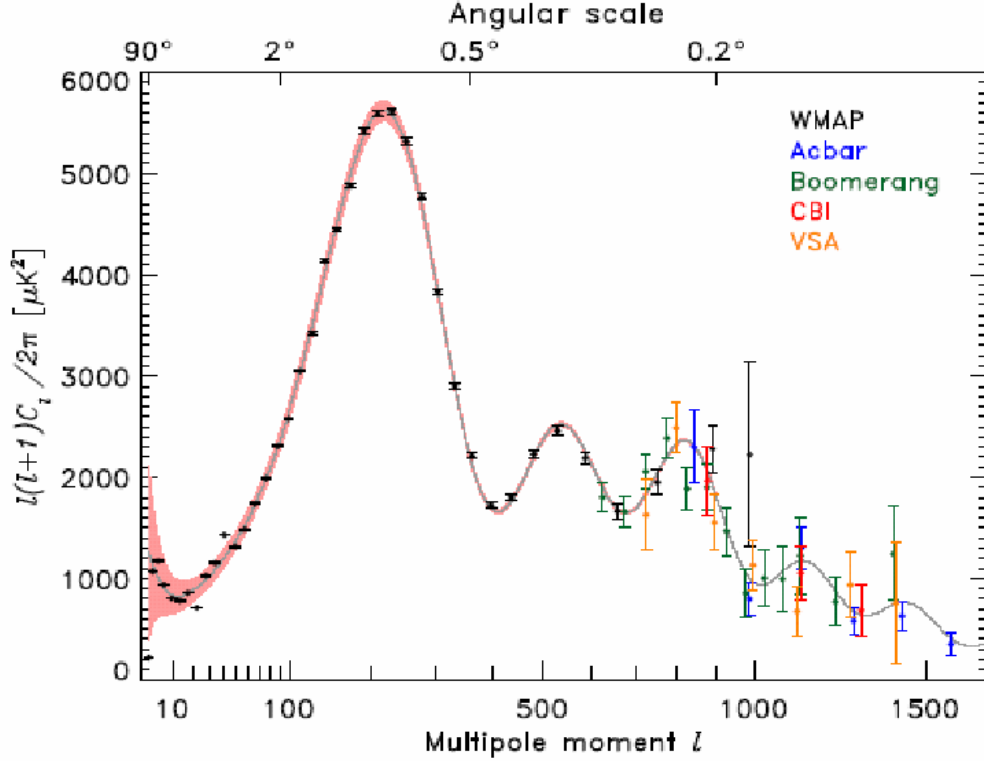


Fig. 3. – Manifestation of sound modulation in the CMB anisotropy spectrum.

branch of the sound perturbations takes advantage at the radiation-dominated stage<sup>(2)</sup>:  $\langle |C_1^{(fin)}| \rangle \gg \langle |C_2^{(fin)}| \rangle$ . By the moment of matter-radiation decoupling at the recombination era, the radiation spectrum appears modulated with typical phase scales  $k_n = n\pi\sqrt{3}/\eta_{rec}$ , where  $n$  is a natural number.

It is these acoustic oscillations that are observed in the spectra of the CMB anisotropy (see Fig. 3, the highest peak corresponds to  $n = 1$ ) and the density perturbations, which confirms the quantum-gravitational origin of the  $S$  mode. We see, the standard cosmological model can begin as follows. "In the beginning was sound. And the sound was of the Big Bang". It differs a bit from the scenario described in the Bible.

The sound modulation in the density perturbation spectrum is suppressed by the small factor of the baryon fraction in the entire budget of matter density. This allows one to determine this fraction independently of other cosmological tests. The oscillation scale itself is an example of the standard ruler that is used to determine cosmological parameters of the Universe. The problem of degeneracy of cosmological parameters reconstructed from observational data hindered scientists from building-up the model of the Universe for many years. But now the acuteness of this problem is looser thanks to

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<sup>(2)</sup> This important result can be explained by the fact that only growing solution is consistent with the isotropic Friedmannian expansion at small times ( $\omega\eta \ll 1$ ).

many independent and complementary observational tests.

To summarize we can say that in principle the problem of the generation of the primordial cosmological perturbations and the large scale structure of the Universe is solved today. The theory of the quantum-gravitational creation of perturbations in the early Universe will be finally confirmed as soon as the T mode is discovered, which is anticipated in the nearest future. For example, the simplest BBS (power-law inflation on massive field) predicts the T mode amplitude to be only as much as 5 times smaller than that of the S mode (which corresponds to  $\gamma \sim 10^{-2}$ ) [8]. Modern devices and technologies are quite able to solve the problem of registering such small signals analyzing observational data on the CMB anisotropy and polarization.

## 6. – On the verge of new physics

Nowadays it became possible to separately determine properties of the early and late Universe from observational astronomical data. We understand how the primordial cosmological density perturbations that formed the structure of Universe emerged. We know crucial cosmological parameters on which the standard model of the Universe is based, and the latter has no viable rivals. However, some fundamental questions of the origin of the Big Bang and of main matter constituents remain unsolved.

Observational discovery of the tensor mode of the cosmological perturbations is a key to building-up the model of the early Universe. In this domain of our knowledge we have a clear-cut theory prediction that is already verified in the case of the *S* mode and can be experimentally verified for the *T* mode in the nearest future.

Giving a long list of hypothetical possibilities where and how to look for DM particles and DM physics theory has exhausted itself. Now it is experiment's turn. The current situation reminds great moments in history of science when quarks, *W*- and *Z*-bosons, neutrino oscillations, the CMB anisotropy and polarization were discovered.

One question is beyond the scope of this review – why Nature is so generous and allows us to reveal its secrets?

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